LCA Case Studies

Application of Life Cycle Inventory Analysis to Fuel Tank System Design

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Abstract

Life Cycle Assessment is becoming an important tool for guiding environmental design improvements in the automotive industry. This paper reports the life cycle inventory profiles for two fuel tank systems based on a collaborative effort between the National Pollution Prevention Center at the University of Michigan, General Motors Research and Development, and the National Risk Management Research Laboratory of the U.S. Environmental Protection Agency. Two 31 gallon functionally equivalent fuel tank systems used on a 1996 light duty vehicle were investigated: a multi-layer HDPE tank with a steel shield and PVC coated steel straps, and a steel tank with a HDPE shield and painted steel straps. Overall, the HDPE fuel tank system is environmentally preferable to the steel tank system based on the set of inventory results presented in this investigation. The Life Cycle Inventory analysis indicated lower energy burdens for the HDPE tank system and comparable solid waste burdens for both systems. The total life cycle energy consumption for the steel and HDPE tank systems were 4.9 GJ and 3.6 GJ per tank, respectively. The energy consumption and most of the air pollutants inventoried occurred as a consequence of the use phase. The solid wastes were generated primarily during the material production phase for the steel tank (13 kg) and during the end-of-life management phase for the HDPE tank (14 kg). This study also highlights data analysis and modeling challenges, including manufacturing and use phase allocation methods.

Keywords: Automotive industry, fuel tank, LCI; HDPE, fuel tank, LCI; LCI, automotive industry, fuel tank systems; fuel tank systems, LCI; product system design, automotive industry, LCI

1 Introduction

Plastic fuel tanks date back to the early 1950's. The success of Volkswagen's use of high molecular weight polyethylene tanks in the early 1970's has considerably influenced the growth of HDPE fuel tanks in North America (Wood, 1991). During the late 1980's and early 1990's, American companies began experimenting with using plastic fuel tanks. Delphi studies forecast that by the year 2000, 40% of all North American-produced passenger cars and light trucks will have plastic fuel tanks and 60% will have steel tanks. By the year 2005, they forecast that 60% of fuel tanks will be made of plastic and 40% will be made of steel (Office for the Study of Automotive Transportation 1996).

Earlier versions of the HDPE fuel tank used fluorination to reduce fuel permeation. With the invention of the coextrusion blow molding process by Krupp-Kautex, plastic fuel tanks are now more permeation-resistant than their predecessors. Multi-layer plastic tanks are able to meet the current stringent US and California evaporative emissions standards, whereas monolayer tanks are not.

A life cycle design demonstration project was initiated following EPA guidelines (Keoleian et al., 1993) with GM to conduct a comparative assessment of a multi-layer HDPE fuel tank system and a steel tank system for a light duty truck with a fuel capacity of 31 gallons. The total life cycle environmental burdens associated with plastic and steel fuel tanks have not previously been fully characterized. Yamato and Mituhara 1997 analyzed the environmental burdens of steel and plastic tanks for material production, manufacturing and end-of-life stages. They concluded that the steel fuel tank posed a greater burden in energy consumption and CO_2 and NO_x emissions. While Yamato and Mituhara recognized the importance of the use phase contributions to the total life cycle burdens, they did not measure the use phase environmental burdens related to the fuel tanks. Fussler and Krummenacher 1991 compiled the life cycle energies for a variety of automotive components. They reported that a 3.4 kg HDPE tank consumed 1135 MJ less energy compared to a 6.7 kg steel tank. The fuel tank systems investigated in the GM Demonstration project included two components in addition to the fuel tank, which were unique to each system. For the steel tank system a stone shield and straps were analyzed and in the case of the HDPE system, a heat shield and straps were inventoried. These components were included in the system boundaries to achieve functional equivalency.

The purpose of this paper is to present the methodology and results of the life cycle inventory analysis from the GM Life Cycle Design Fuel Tank System Demonstration project. Several challenges will be highlighted relating to the data collection and modeling phases of this investigation.

2 Methodology

2.1 Product system

The scope of the analysis includes all tank system components that are unique to each system. For example, the steel tank requires a plastic shield to protect it from environmental exposure, which includes humidity, salt, stones, and many other factors, whereas the plastic tank is inherently more resistant to corrosion and damage due to environmental exposure. On the other hand, for this particular design application, because of component layout, the plastic tank requires a metal (steel) heat shield, whereas the steel tank does not. Furthermore, the straps, which secure the tank to the frame, are different for each fuel system; therefore, they have been included in the study. Other auxiliary components of the fuel system include the sending unit, fuel lines, and fuel filter. These have not been included in the scope because they are common between the two systems. It should be noted however, that not all plastic fuel tank systems require a metal heat shield. The model tank studied in this report requires one because of its orientation on the vehicle frame. Plastic fuel tank systems for other vehicle designs have been designed without a metal heat shield.

For the steel tank system, the fuel tank is plain carbon steel (1008-1010), with a nickel-zinc coating and an aluminum epoxy paint coat. The straps are made of hot dipped galvanized steel with a painted finish. The tank shield is made of HDPE. For the HDPE tank system, the fuel tank is a six-layer plastic structure which consists primarily of HDPE. The six layers of the plastic tank from outer to inner layer include: virgin HDPE mixed with carbon black, a regrind layer which incorporates flash and scrapped tanks, an adhesive layer, an ethyl vinyl alcohol (EVOH) copolymer permeation barrier, an adhesive layer, and finally a virgin HDPE inner layer. The straps for this tank system are also hot-dipped galvanized steel with a PVC coating. The tank heat shield is plain carbon steel.

Both fuel tanks went into production for 1996 full size vans (G-van model). The steel fuel tank has a volume of 31 gallons (117 l) while the HDPE tank is 34.5 gallons (131 l). The HDPE tank weight was normalized to 31 gallons (117 l) so that the two tanks delivered equivalent functionality. The product composition by mass for each functionally equivalent tank system is shown in **Figure 1**. The total weight of the steel and HDPE tank systems (including shield and straps) are 21.92 kg and 14.07 kg, respectively. The comparative analysis was conducted for a vehicle life of 110,000 miles (177,000 km). The boundaries and major assumptions for this study are summarized in **Table 1**.

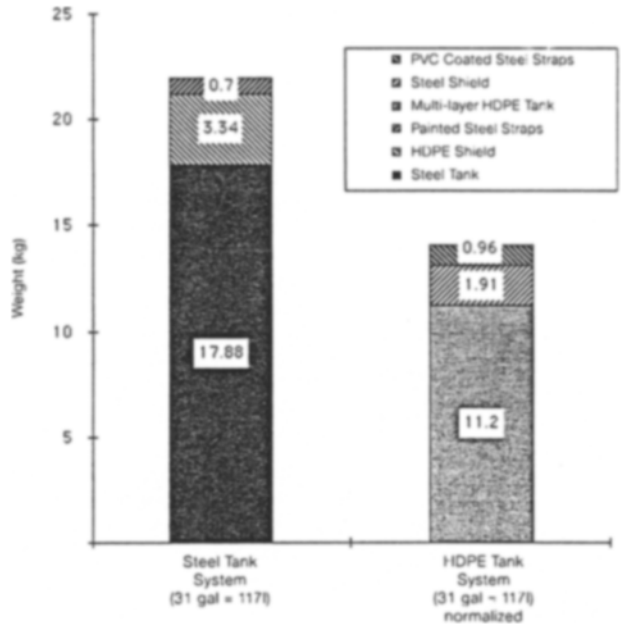

Fig. 1: Composition of fuel tank systems

The major life cycle processes of the steel fuel tank system are illustrated in **Figure 2** (*p. 21*). For this system the steel tank and straps are recycled whereas the HDPE shield is currently disposed in a landfill as part of the automotive shredder residue (ASR). The major life cycle processes of the HDPE fuel tank system are illustrated in **Figure 3** (*p. 21*). The steel shield and straps are recycled in the end-of-life phase whereas the HDPE tank is currently disposed in a landfill as part of the automotive shredder residue (ASR).

2.2 Data collection and analysis

The Life Cycle Inventory analysis was conducted following EPA and SETAC guidelines (VIGON et al., 1993; SETAC, 1991). Environmental data evaluated were material and energy consumption, solid waste generation, and air and water pollutant releases.

2.3 Material production

This investigation relied heavily on European material production data because these data are not yet publicly available from US sources. Production processes are not expected to differ significantly between Europe and the US for the materials investigated herein. Environmental releases could, however, differ significantly due in part to differences in environmental regulations controlling these material industries. Electricity production efficiencies for Europe and the

Table 1: Boundaries and major assumptions for fuel tank systems

LC Stage	Steel Tank	HDPE Tank
Material Production	The paint applied to the steel straps was modeled as steel because of the lack of data on the amount of paint applied (expected to be much less than 1% of the total system material mass) and lack of paint inventory data.	HDPE was substituted for the following components of the multi-layer tank: Carbon Black PE-based Adhesive EVOH PVC applied to straps was assumed to be emulsion PVC
Manufacturing	None of life cycle burdens of process materials were inventoried due to data availability Scrap rate of 2% was estimated for HDPE injection molding process based on generic scrap rate data No scrap was considered to be generated in steel strap fabrication Zinc-Nickel coating and soap lubrication were not included due to data availability Copper is used as a process material in steel tank fabrication. Copper recycling was not inventoried due to data availability Foam pads used for tank distribution were excluded based on mass	None of life cycle burdens of process materials were inventoried due to data availability No scrap was considered to be generated in steel strap fabrication The energy consumption for tank blow molding was based on generic blow molding/injection molding energy data.
Use	Contribution of tank system weight to use phase energy consumption is calculated by assuming that weight is linearly proportional to fuel consumption. No secondary weight savings were estimated Vehicle use phase emissions are the sum of US EPA in-use emission standards for light trucks plus off-cycle emissions Tank system contribution to vehicle emissions is obtained by assuming that emissions are proportional to total vehicle fuel consumption allocated to the fuel tank system; the allocation rule is accurate for CO_2 but for other gases the relationship is non-linear.	
End of Life	All components are considered to be shredded. Shredding fuel requirements were considered independent of the type of material shredded or shape of the part Steel is assumed to be recovered at 100% within each system All HDPE is assumed to be landfilled Preliminary analysis indicated that steel recovered at end of life generated (at least) the amount of scrap steel needed for steel making. No credit was given to the system for any steel recovered in excess of the amount needed for steel making	

US are very comparable; hence this factor may not strongly affect the representativeness of the European inventory data for US conditions. For example, the electricity production efficiency for the national grid in the US has been reported as 0.32 (Franklin Associates, 1991) whereas the efficiency for the UCPTE (Union for the Connection of Production and Transportation of Electricity) was found to be 0.378 (FOEFL, 1991). Regional differences in electricity production within the US and Europe, however, are much greater than this difference and could be significant. The influence

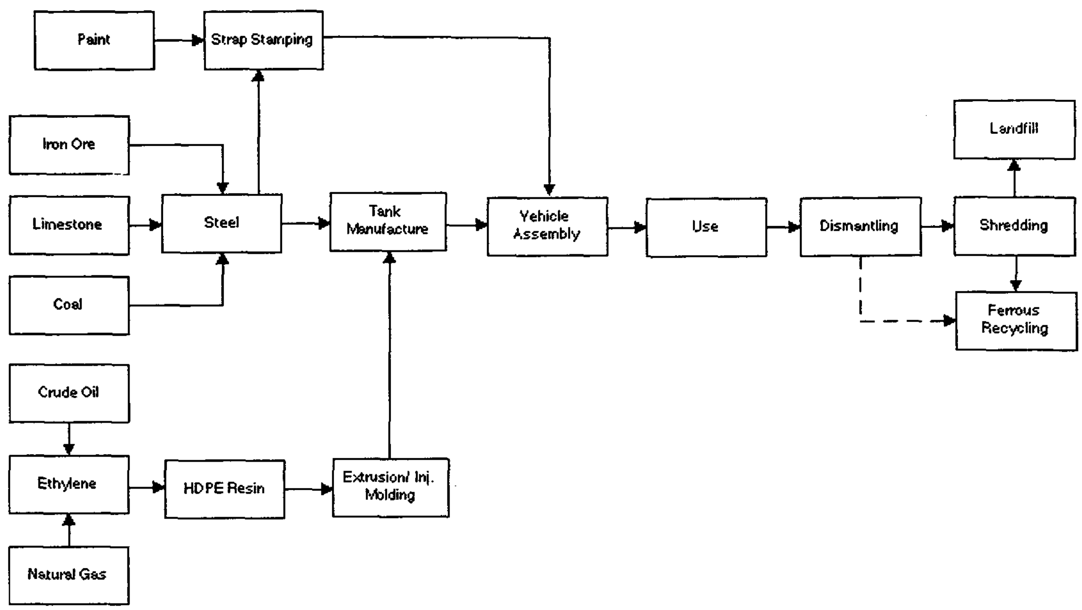

Fig. 2: Steel fuel tank system

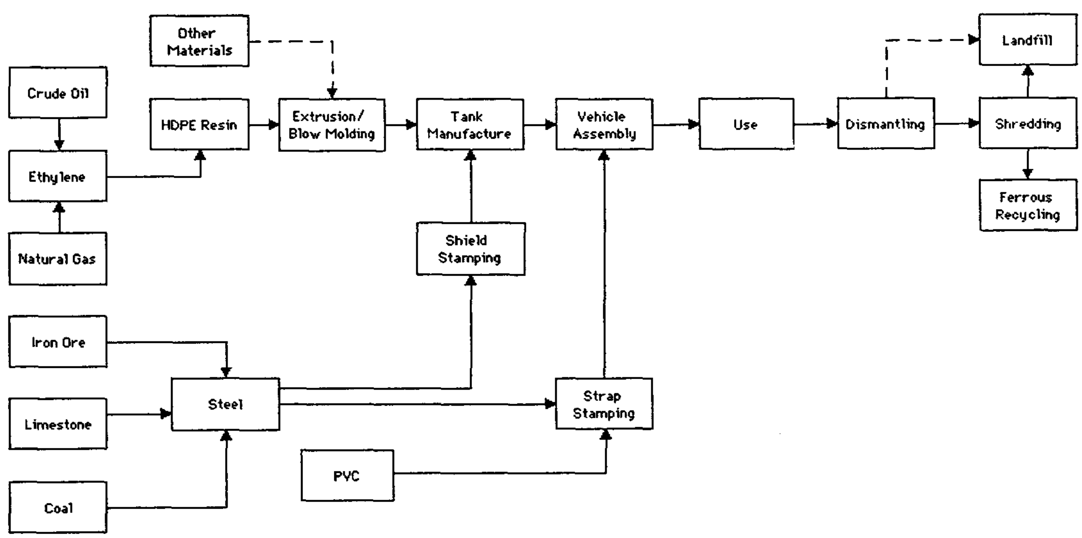

Fig. 3: HDPE fuel tank system

on the electricity production efficiency is minimal because electricity accounts for less than twenty-five percent of the total material production energies for steel and HDPE (FOEFL, 1991; BOUSTEAD, 1993).

(1) Steel

Environmental data for the material production of plain carbon steel were approximated using data for tin-plate steel from a European environmental database of packaging materials (FOEFL, 1991). The data includes hot and cold rolling of the steel to produce sheet. The nickel-zinc coating was not included in the scope because of data availability. The emissions related specifically to the aluminum epoxy paint application were excluded from the scope due to insufficient data. The data include the burdens associated with the tinning of steel, which could not be disaggregated from the inventory data set, and the reprocessing of scrap steel. The steel had a tin content of 0.4 percent for this data set. Additionally, the data assumes a transport distance of 7500 kilometers for iron ore transport to Germany. This distance would be considerably shorter for steel produced in the US. The total transportation energy requirement,

however, is only 5.5% of the total material production energy for steel (FOEFL, 1991). Consequently, this factor would not significantly impact the final results.

(2) HDPE
Environmental data for the material production of HDPE were obtained from the European Center for Plastics in the Environment now known as the Association of Plastic Manufacturers in Europe's (APME) Technical and Environmental Center (BOUSTEAD, 1993). The data is for virgin HDPE. Based on data availability, the multi-layer tank was modeled as 100 percent HDPE. The tank adhesive layers and EVOH barrier material constitute less than 1% of the total tank material on a volume basis.

(3) PVC
Environmental data for the material production of PVC were obtained from APME (BOUSTEAD, 1994). The data is based on emulsion polymerization since this type of PVC is used in dipping applications.

2.4 Manufacturing

(1) Steel Tank
The main manufacturing operations include stamping, trimming and piercing, washing, welding, quality control testing, and component assembly. The manufacturing process begins with the stamping of pre-cut cold rolled steel. Environmental data for steel tank manufacturing were obtained from GM. Eighty percent of the water used in this manufacturing process is consumed during soap lubricant washing. Additional wastewater comes mainly from the cooling and chilling system from the welding operation. The wastewater used in this washing operation is sent to a water treatment facility within the manufacturer's industrial complex, and is combined with wastewater from four other plants.

The tank is formed by joining together two stamped pieces using resistance welding. Air emissions from welding consist of manganese, nickel, chromium, zinc, particulates and hydrocarbons from the aluminum-based epoxy paint coat.

Table 2: Atmospheric emissions for steel tank manufacturing

Emission†	Amount (g/tank)
Mn	0.0868
Ni	0.0658
Cr	0.0500
Zn	0.0605
Particulate	1.8410
Hydrocarbon	0.6840

Source: (GM, 1996)

Emission factors for these air pollutants based on plant data are provided in **Table 2**. Copper used as a welding aid is recycled and not consumed to any appreciable degree.

Each tank is water tested for leaks as a quality control mechanism. There are two possible failure modes. One failure mode is known as a seam leak due to hot welding. It is repaired by soldering the leaking area with a 99% Sn/1% Ag-based solder. The other possible failure mode is an edge leak which is due to cold welding. Only 10% of edge leaks are repairable, the remaining 90% are scrapped. 100% of tanks that are rejected because of edge leak failure are recycled. Finally, the tanks are prepared for shipping to the assembly plant via rail.

The total amount of scrap generated in steel tank manufacturing is 580 metric tons per 171,000 tanks per year. This scrap includes tank trimmings, tanks that fail quality control tests, and assembly plant returns. The overall scrap rate is 18.9% and the total primary energy consumption for steel tank manufacturing is 2.7 MJ/kg (GM, 1996).

Waterborne emissions result primarily from tank washing to remove lubricant. As previously stated, the wastewater from this washing step is combined with wastewater from four other plants and is treated in a wastewater treatment plant. Eighty percent of the treated wastewater originates at the fuel tank manufacturing plant. Emissions include oil and grease, zinc, nickel, tin, silver, and copper. **Table 3** summarizes the levels of these emissions after treatment. One hundred percent of the emissions from this wastewater treatment plant were allocated to the tank system, despite the fact that the wastewater analysis includes emissions from four other plants. Hence these emissions represent the upper limit of waterborne releases. The water emissions data shown in **Table 3** is based on the monthly average concentrations measured in 1995.

Table 3: Upper limits for waterborne emissions for steel tank manufacturing

Emission[a]	Amount (mg/tank)
Copper	0.029
Nickel	0.944
Zinc	15.90
Oil and Grease	170.8

Source: GM, 1996
[a]based on emissions data from multiple plants

For steel strap manufacturing, the data scope includes steel stamping. Steel stamping energy data were obtained from the International Iron and Steel Institute (IISI, 1994). No scrap was assumed to be generated in producing the straps. For HDPE shield manufacturing, the data scope includes

injection molding. HDPE injection molding energy requirements were estimated from generic data for polyolefins blow molding/injection molding (WYTHE, 1996). No scrap was assumed to be generated.

(2) HDPE Tank
Environmental data for HDPE tank manufacturing were obtained from GM sources and the Steven's Institute of Technology (WYTHE, 1996). The data scope includes tank blow molding, machining, and auxiliary component attachment. Energy requirements for HDPE tank manufacturing were based on HDPE blow molding/injection molding energy requirements obtained from the Steven's Institute of Technology (WYTHE, 1996). Particulate and hydrocarbon air emissions were estimated from Barlow (BARLOW and CONTOS, 1996).

The main manufacturing stages for the plastic tank include extrusion and blow molding, regrind recycling, cooling, machining, component attachment, and quality and safety testing. All finished tanks are placed on shipping racks and are sent to the assembly plant by truck. The overall scrap rate for HDPE tank manufacturing is 1.7% and the total primary energy consumption for plastic tank manufacturing is 14.0 MJ/kg (GM, 1996, Franklin Associates, 1992). The overall scrap rate includes plastic waste generated in production start-up and regrind waste. Shut-down waste, a significant waste source, was not included in the overall scrap rate because this data was not available.

Process materials for tank manufacturing include water for cooling machinery and leak testing, machining and lubricating fluids, ethylene glycol for drop testing, and LDPE for purging the EVOH extruder. According to the manufacturer, water is sent directly to the drain without any pretreatment. The ethylene glycol is recycled and reused. The LDPE used to purge the EVOH extruder is landfilled because it cannot be incorporated into the product.

For steel straps and shield manufacture, the data scope includes steel stamping. Steel stamping energy data was obtained from the International Iron and Steel Institute (IISI, 1994). No scrap was assumed to be generated. The steel straps are coated with 30 grams of PVC per strap. The mass of PVC coating was estimated from the strap geometry.

Three sources of scrap formation exist during the manufacture of plastic fuel tanks, including: 1) flash, i.e., excess blow-molded material, 2) scrapped fuel tanks, i.e., tanks that fail to meet quality specifications, and 3) waste material generated during start-up and shut-down. This scrap consists of the components of the multi-layer fuel tank, i.e., HDPE, EVOH, and the polyethylene-based adhesive. A large portion of shut-down waste consists of LDPE. Residual amounts of LDPE are present during start-up; therefore, these molds cannot be incorporated as regrind and must be landfilled.

The multilayer tank manufacturer estimates that flash represents 30% of fuel tank weight. Flash is reground and does not contribute significantly to solid waste leaving the manufacturing facility. However, approximately 1.5% of all reground material is landfilled. Tank scrappage rates for the multi-layer tank were not available from the manufacturer so data from monolayer tank manufacturing was used as a rough estimate. The multilayer tank manufacturer estimates that approximately 249.5 kg of waste material is generated during each start-up of a production run. At full G van tank production rates, approximately 2100 tanks will be manufactured per production run. This represents 0.119 kg of waste material per tank, or 2744 kg of landfilled material per year, assuming there are eleven start-up cycles per year. **Table 4** summarizes the main sources of plastic waste and the amount generated per tank during manufacturing.

Table 4: Solid waste summary

Source of scrap	Mass (kg per tank)
Flash	0.05
Scrapped tanks	0.016
Start-up wastes	0.119
Shut-down	NA

2.5 Use

The use phase environmental data were calculated for an assumed tank life of 110,000 miles (177,000 km) for a 1996 G Passenger Van with the weight and fuel economy data indicated in **Table 5**. Functional equivalency was defined as:

Table 5: Weight and fuel economy data for 1996 G passenger van

Parameter	Metrics
Test weight	2766 kg or 6100 lb
Fuel economy	Steel Tank 16.40 mpg or 14.34 L/100 km
	HDPE Tank 16.42 mpg or 14.32 L/100 km
Weight to fuel economy correlation	10% weight reduction ≡ 4.38% fuel consumption reduction*

Source: (GM 1996)
*Derived from fuel economy data and the differential fuel tank weights

A tank required to provide sufficient fuel to propel the model truck 450 to 600 highway kilometers between refueling over an eleven year expected life of the vehicle.

The contribution of the tank system to vehicle fuel consumption (F) was obtained using the following correlation:

$$F = M_T \times L \times \left[\frac{FE}{M_V}\right] \times \frac{\Delta f}{\Delta M} \qquad (1)$$

Table 6: Fuel consumption and use phase energy contribution of fuel tanks sstems

Fuel Tank System	Weight (kg)	Allocated Fuel Consumption F (liter)	Allocated Fuel Consumption F (gallons)	Energy (GJ)
Steel	21.92	88.18	23.30	3.71
HDPE	14.07	56.60	14.95	2.38

where,

F = fuel (liters) consumed over the life of fuel tank system

M_T = mass of the fuel tank system

M_V = test weight (mass) of vehicle

$\frac{\Delta f}{\Delta M}$ = fuel consumption correlation with mass

FE = fuel economy (liters/km)

L = life of tank system (km)

The lifetime fuel consumption for the two tank systems are given in **Table 6**. **Table 6** reports primary energy consumption in GJ which includes precombustion and combustion energies associated with the total fuel cycle of gasoline. The primary energy factor for gasoline is 42.03 MJ/l (KAR and KEOLEIAN, 1996).

Emissions

The vehicle emissions analyzed in this study include in-use emissions (tailpipe and evaporative) and precombustion emissions associated with the gasoline fuel cycle. With the exception of carbon dioxide, air emissions data for vehicle fuel combustion are based on a combination of Tier 0 emission standards for light duty trucks and off-cycle emissions (i.e., emissions that occur from driving at high power) as reported by ROSS (ROSS and GOODWIN, 1995). **Table 7** shows these values for the G van equipped with a steel tank. The values in **Table 7** do not include pre-combustion emissions. The Tier 0 emissions standards require that exhaust emissions not exceed the standards for 120,000 miles (193,000 km) of vehicle life.

CO_2 emissions are estimated at 2.338 kg per liter of gasoline combusted (KAR and KEOLEIAN, 1996). The tank contribution to total vehicle air emissions is based on the total fuel consumption allocated to the tank using the following relationship:

$$m_e = m_e' \times F \div FE \quad (2)$$

where,

m_e = life cycle emission per fuel tank system

m_e' = emission factor (g/km)

2.6 End-of-life management

For the purposes of this study all components of both tank systems are assumed to be shredded, all steel is recovered and subsequently recycled at 100%, and all plastic is landfilled. Energy requirements (108 kJ/kg) for shredding were obtained from (KAR and KEOLEIAN, 1996), (SULLIVAN and HU, 1995). The shredding data was assumed to be independent of material or part geometry.

Table 7: In-use emissions (tailpipe and evaporative) estimates for 1996 G van (equipped with a steel tank)

	CO gpm (g/km)	HC gpm (g/km)	NOx gpm (g/km)
Tier 0 Standards	10.0 (6.2)	0.8 (5.0)	1.7 (1.1)
Off-cycle Emissions	7.9 (4.9)	0.12 (0.07)	0.3 (0.2)
Total Average Lifetime Emission Rate	17.9 (11.1)	0.92 (0.57)	2.0 (1.2)
Total Emissions for 110,000 miles (177,000 km) in kg	1969.0	101.2	220.0

Source: [CFR, 1994], [ROSS and GOODWIN, 1995].

2.7 Transport

Transport distance data for the linkages between manufacturing operations were obtained from the GM project team and estimates for end-of-life management were obtained from the American Plastics Council (American Plastics Council, 1994). Transportation fuel efficiency and emissions data were obtained from Franklin Associates (FRANKLIN, 1992). The transportation energy for manufacturing operations was 31.7 MJ per steel tank and 54.1 MJ per plastic tank. For end-of-life management, the transportation energy was 6.4 MJ per steel tank and 8.2 MJ per plastic tank. A detailed analysis of each transportation step is provided elsewhere by the authors (KEOLEIAN et al., 1997a).

3 Results

3.1 Life cycle energy

Figure 4 shows the life cycle energy profile for each fuel tank based on a vehicle life of 110,000 miles (177,000 km). (The primary energy consumed for each stage of life cycle is indicated in units of GJ/tank.) For both tank systems, the use phase accounts for the majority of the energy consumed. Over the 110,000 miles (177,000 km) traveled, the steel and HDPE tanks (including shield and straps) are responsible for the consumption of 88.2 and 56.6 liters of gasoline, respectively. For comparison, the G passenger van consumes 25,390 liters when equipped with a steel fuel tank system; whereas, when equipped with an HDPE fuel tank system, the van consumes 25,359 liters.

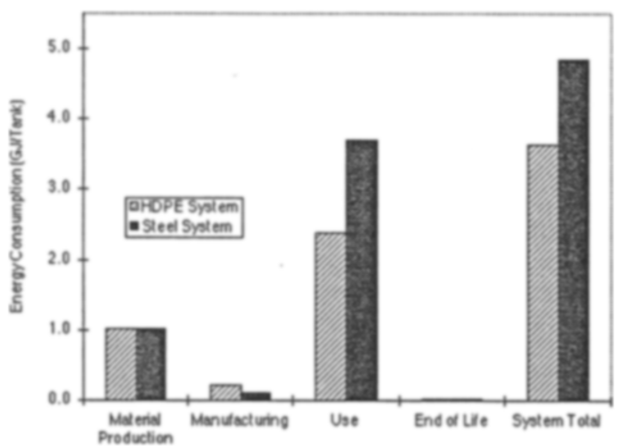

Fig. 4: Life cycle energy consumption for HDPE and steel fuel tank systems

For the steel tank design, the use phase constitutes 76 percent of the total life cycle energy. For the HDPE tank, it is responsible for 66 percent of the total energy. Although less HDPE material is used in the fabrication of one tank relative to steel, the higher specific energy for HDPE (81 MJ/kg) compared to steel (33.5 MJ/kg) yields comparable total material production energies for each system. The manufacturing for the HDPE tank system requires 85 percent more energy than for steel which is a consequence of greater energy input for HDPE blow molding compared to steel stamping. End-of-life management energy is relatively negligible. The current practice of landfill disposition for the HDPE tank, however, results in a significant loss of energy in the form of the embodied energy of the material.

3.2 Life cycle solid waste

The solid waste generated across each stage of the fuel tank life cycle is shown in **Figure 5**. The material production and end-of-life management stages indicate opposite trends for the two systems. The relatively high solid waste from the production of steel is associated with precombustion processes (e.g., coal mining) and slag, whereas the high solid waste from the plastic system is associated with end-of-life management.

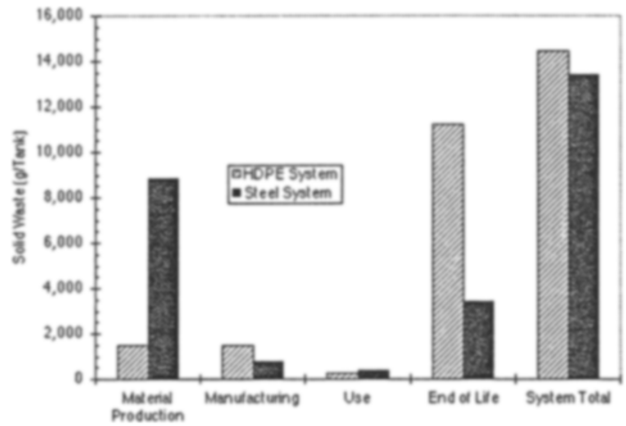

Fig. 5: Life cycle solid waste generation for HDPE and steel fuel tanks

The Swiss Ecobalance study (FOEFL, 1991), which was used to estimate solid waste generation from steel production, did not account for wastes from mining iron ore. This study also reported that a significant fraction of the slag was reused in applications such as road construction (FOEFL, 1991). This practice is also followed in North America. Solid waste from the end-of-life management stage was evaluated using a model describing current practices. It is recognized that the infrastructure may change over the next decade when a majority of these tanks will be retired. Scenarios involving HDPE recycling, energy recovery, and tank reuse could significantly impact the results.

3.3 Life cycle air emissions

The cumulative life cycle air emissions of carbon monoxide, NOx, particulate matter (PM), hydrocarbons (HC) and SO_2 are presented in **Figure 6**. In all cases, emissions were higher for the steel tank system compared with the HDPE tank

system. The distribution of air pollutant emissions in each life cycle stage is presented elsewhere by the authors (KEOLEIAN et al., 1997a). In general, the use phase dominated the life cycle air emissions of these pollutants. Particulate matter is an exception for the steel fuel tank system. Total carbon dioxide emissions correlate well with total life cycle energy consumption; 295 kg of CO_2 is released for the steel fuel tank system compared with 191 kg of CO_2 for the HDPE fuel tank system. This correlation is expected because of the large fraction of energy originating from carbon based fossil fuels. The carbon dioxide emissions account for a majority of the greenhouse gas emissions which have potentially catastrophic effects on climate.

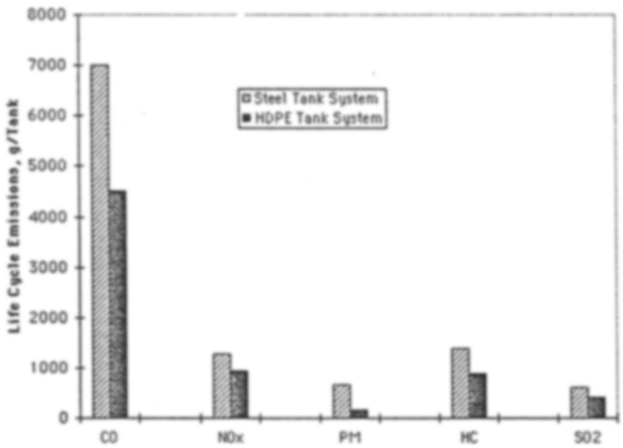

Fig. 6: Cumulative life cycle air emissions

The contribution of the fuel tank to the total vehicle use phase emissions was estimated assuming that these emissions are proportional to gasoline consumption. Although this relationship is valid for carbon dioxide, this allocation is probably not accurate for the evaporative emissions and pollutants that are controlled by the catalytic converter. The use phase emission factors used in this study represent a significant increase over the EPA certified vehicle emissions for the new model G and cutaway vans. This difference has also been corroborated by EPA (KEOLEIAN et al., 1997b).

Carbon monoxide is primarily a mobile source pollutant originating from vehicle exhaust. In the United States, two serious and 39 moderate carbon monoxide non-attainment zones were reported by EPA in 1995. NO_x emissions and hydrocarbon emissions contribute to ozone formation which is a major urban air quality problem in several areas. Twenty-two serious ozone non-attainment zones were cited by EPA. However, it should be noted that CO and ozone non-attainment is largely a regional issue. The total life cycle air emissions of CO and ozone precursors are distributed over a large geographical area and time frame. Hence, direct relationships between these emissions and the problems of regional smog are difficult to define. Relatively large amounts of PM emissions occurred in the material production phase of the steel tank system. The use phase PM and SO_2 emissions result from upstream processes in the total gasoline fuel cycle (precombustion). For SO_2 about half of the life cycle emissions occurred in the use phase while most of the balance occurred in material production and manufacturing stages for both tank systems.

3.4 Life cycle water effluents

The cumulative life cycle waterborne emissions of suspended solids, BOD, COD, oil and grease, and metals are presented in **Figure 7**. The total life cycle dissolved solids emissions were 890 g for the steel fuel tank system compared to 560 g for the HDPE fuel tank system. The results show greater waterborne releases for the steel fuel tank system compared to the HDPE fuel tank system for all pollutants except metals.

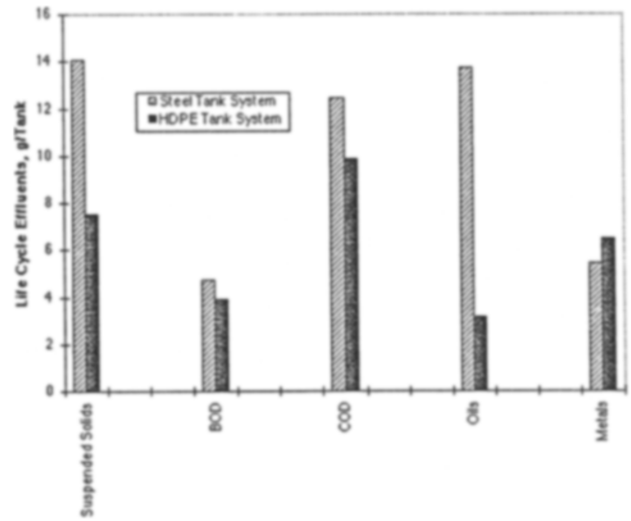

Fig. 7: Cumulative life cycle water emissions

The distribution of waterborne emissions in each life cycle stage is presented elsewhere by the authors (KEOLEIAN et al., 1997a). For dissolved solids, emissions occur primarily in the use phase. These emissions are derived from the refineries which produce the gasoline used in the vehicle. For suspended solids, oil and grease, and metal emissions, the material production phase is the largest source. The aggregate form of the data for both steel and HDPE do not allow us to determine the precise sources of these emissions. For waterborne metals, the manufacturing phase is also responsible for a significant source of emissions. These emissions can be traced back primarily to electricity production for steel stamping and HDPE blow molding. In the steel tank system, steel stamping plant releases represent a very small portion of the total manufacturing releases.

4 Conclusions and Recommendations

The environmental profiles of the steel and HDPE fuel tank systems differ significantly. Overall, the HDPE fuel tank

system is environmentally preferable to the steel tank system based on the inventory results from this investigation. The total life cycle energy consumption for the steel and HDPE tank systems was 4.9 GJ and 3.6 GJ per tank, respectively. A major fraction of this energy was consumed during the use phase. Conversely, the solid waste burdens associated with the fuel tank systems were concentrated in the material production and end-of-life management phases. The steel tank system generated approximately 13 kg of total solid waste per tank while the HDPE system generated approximately 14 kg. These differences are not significant within the expected uncertainty of this analysis. The analysis indicates that most of the solid waste associated with steel is generated in the material production phase whereas the HDPE solid waste is concentrated in vehicle end-of-life management.

The lighter weight of the HDPE results in significant savings in use phase energy relative to the steel for this particular application. This contributes to an overall lower life cycle energy requirement for the HDPE tank system. The life cycle solid waste generation for both systems is comparable. Currently, the HDPE tank is not recyclable in the end-of-life management stage. On the other hand, in the material production phase, the steel tank system contributes significantly more solid waste compared to the HDPE system, according to the published data sources available for this study. Air and water release data is much less reliable, but in several pollutant categories, the use phase burdens associated with the full gasoline fuel cycle dominate. In these instances, the HDPE tank system has lower burdens.

The sensitivity of the results with respect to the steel material production energy was tested previously (Keoleian et al., 1997a). A 20% improvement in the material production energy to 26.7 MJ/kg would reduce the total life cycle energy for the steel tank system by only 2.9% to 4.7 GJ. A significant reduction of the steel tank mass is required to achieve a lower total life cycle energy relative to the HDPE tank system energy. A one-third reduction in the steel tank mass would be necessary to achieve the same total life cycle energy of the HDPE tank system. Use phase performance requirements may prohibit the necessary reduction in wall thickness of the steel tank.

This Life Cycle Inventory presented several challenges in modeling and data collection. The inventory combined plant data with process specific emissions, energy and waste factors from published sources. The lack of process data on nickel/zinc coating of steel indicates that the steel fuel tank burdens were understated. This condition strengthens the conclusion that the HDPE tank is environmentally preferable to the steel tank. Steel stamping water effluents were characterized using an upper limit to the actual plant releases. The upper limit was used because effluent data for several facilities could not be disaggregated. In this case, waterborne metal and oil/grease manufacturing emissions were overstated. For oil and grease, however, the manufacturing emissions for the steel tank system were insignificant relative to material production and use phase emissions.

The lack of available inventory data for steel and HDPE for material production in the US is a potential limitation of this study. European data were the best available data at the time of this study. While the use of European data introduces additional uncertainty into the results, the relative distribution of environmental burdens across the life cycle for each tank system could not be characterized without these data. Material databases are currently being developed in the US which will be available for future LCAs. The discrepancy between US and European databases can then be evaluated and their implications on these life cycle inventory results can be ascertained.

The vehicle air pollutant emissions in the use phase dominated the total life cycle burdens, therefore, the methodology for evaluating these emissions was very significant. Tier 0 standards were supplemented with off-cycle emissions not captured in EPA test procedures. The Tier 0 standards represent a maximum emissions level and therefore the use phase emission results should be an upper limit to the expected in-use vehicle emissions. The in-use emissions modeling did not account for differences in the evaporative emissions contributed by the HDPE and steel fuel tanks. However, diurnal test results indicated that these emissions are comparable (GM, 1996).

Although a comprehensive set of life cycle inventory data is often not available, modeling techniques demonstrated in this investigation provide a useful approach towards characterizing the relative environmental performance of two different product systems. The project team experienced difficulties in collecting inventory data from the Tier 1 supplier of plastic fuel tanks. In contrast, manufacturing data for steel tanks was readily forthcoming from a GM facility. One possible strategy for facilitating data collection is to seek the commitment of key stakeholders to participate in the initial phase of the project. Furthermore, the results of this study provide a framework for OEM's to develop a simplified set of metrics for comparing multi-layer HDPE and steel fuel tank systems for other vehicle platforms. Many of these metrics can be computed using energy, emissions, and waste factors evaluated in this investigation. These metrics would address major burdens in the fuel tank life cycle and would reduce resource requirements for data collection and analysis.

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